THE EFFECT OF LENGTH OF PIPE ON AIR LIFT PERFORMANCE

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CHAPTER I

INTRODUCTION

The air lift pump is becoming more important year by year for lifting water from deep wells. Its field of usefulness is constantly being enlarged, and engineers are beginning to realize that the air lift method of pumping, although not quite as highly efficient as compared with some other methods, is a very important one, owing to the many important advantages it possesses over other methods, in pumping large quantities of liquids from wells of small bore, and on account of other features which will be discussed in succeeding pages. It is safe to say that, under proper conditions and good design, all things considered, the expense of operation of the air lift will compare favorably with any other method of pumping.

The air lift is found in municipal waterworks, irrigation works, breweries, ice factories, dye-works, packing houses, and numerous other places.

Despite the fact that the air lift pump is of universal applicability, there is little known by engineers concerning its proper design and installation. This is primarily due to the scarcity of literature on the subject, and then, too, the system is so very simple that at first sight it does not seem to merit the thought and analysis that other proven mechanical devices receive.

Numerous tests have been conducted by manufacturers of compressors on patented devices and the use of these devices in connection with air lift pumping plants have been made,

but the information gained from such tests has not been made public. Notwithstanding the fact that the method of lifting liquids by air has been known for over a century and has been used considerably in plants of various sizes and for various purposes, the amount of reliable data available to the practicing engineer is indeed very meager.

With the purpose of supplying the demand for reliable data, the authors have made a series of runs or experiments on the air lift and have presented all pertinent data herewith.

It is the opinion of the authors that the air lift method of pumping is by far the best method of lifting water from deep wells.

Historical.

The first application of compressed air to lifting water is to be found in the Book of Heron. The arrangement, which there is not time to explain in detail, is to be found in Iven's book on "Pumping by Compressed Air," pages 90 and 91. The arrangement is known as the "Fountain of Heron." The "Fountain of Heron" was used in the mines of Chemnitz, Hungary, about the middle of the eighteenth century.

A Germ n mining engineer named Lascher performed some laboratory experiments on an air pumping station of his own design in the year 1797. He published the results of his tests in a pamphlet called, "Aerostatisches Kunstgezeng." His invention was not put into practical use until about one-half a century later. In 1864, an American mining

engineer named Cockford used what was probably the first practical ap lication of the air lift pump. He succeeded in pumping oil from wells in Pennsylvania.

On May 23, 1865, A. Brear was granted a patent on an "oil ejector" which was in reality an air lift pump. About the same time Siemans experimented with the air lift in England.

On October 19, 1880, J. P. Frizell obtained a patent on an airlift which grew out of his invention of a method of compressing air, on which he received a patent in January, 1878.

In 1885, Werner Siemens used an air lift pump for draining a mine shaft near Berlin. In the same year Laurent, and, in 1886, Goudry, used an air lift for pumping sulphuric acid. They called their pump an "emulseur."

Dr. J. G. Pohle was the first to use the term "air lift" as applied to the above described method of pumping, in his specifications for a patent, which was obtained in December, 1892. The chief distinction between Dr. Pohle's pump and Frizell's lies in the method of introducting the air. To quote his own words, "The invention . . . consists in improved processes and apparatus whereby the compressed air is delivered in bulk into the lower end of the water eduction pipe, and the water and the air are caused to ascend through said pipe in distinct alternate layers of definite dimensions."

In the specifications of his patent, Pohle explains his understanding of the working of his pump as follows:

"I have discovered that when air of suitable pressure is allowed to enter in a constant stream and in suitable quantity into an eduction pipe at or near its lower end when it

is submerged in water, while its upper end rises above the water about the same distance that its lower end is submerged, the compressed air thus introduced will at first expel the standing water from the pipe in an unbroken column free from air, and subsequently, by the continued inflowing of the compressed air under a pressure just sufficient to overcome the resistance of the water outside of the eduction pipe, it will arrange itself in alternate layers with the water, while the latter flows into the lower end of the eduction pipe by force of gravity until it is discharged at the upper or exit end of the pipe. This alternate interposition of determinate quantities of air between the also determinate quantities of water elongates the entire column of air and water, this facilitating, without materially adding to the weight of the column, the discharge of the water at a higher level than would be the case were these air sections or layers absent. I have also discovered that under the above mentioned conditions, the compressed air will not escape through the water overlying it, and also that the water overlying the compressed air will not fall back through the underlying air while both are in upward motion, but find that the elasticity stored in the compressed air layer, pressing alike in all directions, forms a temporary water-tight piston, which lifts the water above it to its final discharge without appreciable loss by leakage or so-called "slip", while this compressed air piston, after having expended its elastic energy in work of lifting water, is dispelled with only a practically unimportant loss of power."

This theory is not substantiated by the authors. It is believed, and the experiments performed by the authors and others tend to show that there is "slippage", and that though there may be successive layers of air and water, the bucket of water is in reality a mixture of fine bubbles of air and water.

Many other patents have been taken on air lift pumps, but they are too numerous to mention.

The Principle of the Air Lift Pump.

Just exactly what action goes on in an air lift pump is not thoroughly known. In the opinion of the authors, the action differs considerably under the various conditions of operation. The basic principle on which the pump operates is, however, comparatively simple.

A very good illustration of the principle of the air lift pump is given in "Bulletin of the University of Wisconsin, Engineering Series, Volume 6, Number 7." The illustration and explanation follow:

First, consider a vertical pipe, open at both ends and partly immersed in a liquid, as shown in Fig. 1(a). The liquid will stand at the same height inside and outside of the pipe. Assume that a block of material, like cork or wood, lighter than the liquid, made to fit the pipe snugly, but able to move without friction, is made to replace part of the liquid near the bottom of the pipe. The hydrostatic pressure on the under side of the block is now greater than the combined weight of the block and the liquid above

it. The block and the liquid in the pipe will, therefore, be pushed up in the pipe, as shown in Fig. 1(b), until the head h balances the difference between the weight of the block and the weight of an equal volume of the liquid. If more blocks of the light solid matter be introduced into the pipe, the liquid will be raised a distance h for each block until the top of the pipe is reached, when an overflow of liquid and blocks will occur, leaving an unbalanced head in the pipe, which would keep up the discharge as long as the supply of liquid and blocks was kept up at the bottom of the pipe. In the Pohle air lift system, the claim is made that the pump works as described above, with the exception that compressed air is used instead of a light solid, and that work is done by the expansion of the air as it is relieved of the weight of the liquid when approaching the top of the pipe.

A closer approximation is made to usual working conditions in an air lift pump by the illustration in Fig. 1(c). In this case the block of light material, cork, wood, or air does not entirely fill the cross-section of the pipe. By virtue of its bucyancy, it will tend to rise in the pipe and the liquid in the pipe will tend to flow down past it. The height h, to which the water rises in the pipe in this case, represents the head necessary to force the liquid down through the restricted passage-way past the block. The same conditions would obtain if the single block nearly filling the pipe were replaced by a large number of small blocks. It

would require some head h to overcome the resistance offered to the liquid in its flow between the small blocks or between the blocks and the pipe walls. If a sufficient quantity of small blocks or air or other light material are inserted, the head h will reach the top of the pipe, and will cause a discharge of the liquid. The flow of the liquid down past the buoyant material is called the slip of the pump. It is the cause of a considerable loss of energy.

A commonly accepted theory of the principle of operation of the air lift pump may be had by considering that the air bubbles, in rising through the water in the discharge pipe, reduce the specific gravity of the mixture and therefore the weight of the column, causing an unbalanced condition between the column inside and outside of the tube. The excess pressure at the base of the column due to the external water pressure, therefore, forces the mixture above the supply level and out of the top of the pipe. This excess pressure increases with the depth of submergence of the pipe, and the latter must be regulated to suit the height of delivery.

Theory of the Air Lift.

Numerous attempts have been made to develop mathematical theories of the air lift pump, but without satisfactory results. There is no single complete theory which is entirely satisfactory. Perhaps this is due to the fact that it is almost impossible to derive truly accurate formulae

expressing the air lift theory, because of the many uncontrollable variables met with. What are probably the best theories thus far advanced are those of Professor Elmo G. Harris in "Compressed Air", and Dr. H. Lorenz in "Zeitschrift des Vereines Deutscher Ingenieure," Vol. 53.

The theories of these two men will be briefly presented in the following paragraphs, and theories of a few others will be mentioned as a reference.

Harris's Theory.- Professor Harris made a number of experiments on the air lift with the purpose of obtaining a rational formula by which a pump would be designed intelligently, and on which experiment would be based. His discussion of the subject was published in the Journal of the Franklin Institute, Vol. 140, page 52, July, 1895. Later, in his book on compressed air, published in 1910, Professor Harris modified his original theory.

In drawing his formulas for the design of a pump, the work done by the air is divided into four parts by Professor Harris, as follows:

(1) The kinetic energy in the liquid discharged at the top of the pipe.

(2) The energy necessary to raise the liquid to the top of the discharge pipe.

(3) The energy lost by the liquid slipping down by the bubbles.

(4) The energy consumed by friction in passing through the pipe.

Theoretical expressions may be found for each of the above quantities. The equation for slip is much too complicated for use in general practice, so an approximate formula based on a number of assumptions may be derived. In the fourth term, the value of the friction factor is assumed, as is the relation of loss to velocity. It is impossible to verify the correctness of the individual terms for losses by experimental means, because the losses due to slip and friction could not be ascertained under working conditions, and since the formulas are very complicated and difficult to use, they will not be given here, but can be found in the references given above.

Lorenz's Theory.- A very good simple mathematical theory of the action of the air lift pump was published by Dr. H. Lorenz in "Zeitschrift des Vereines Deutscher Ingenieure" Vol. 53, page 545, April, 1909. He deduced a number of formulae which take account of the losses of energy occasioned by slip, pipe frictions, etc., and being comparatively simple, they are therefore of practical use in designing air lift pumps, provided the experimental coefficients are known. Dr. Lroenz did not take account of all losses, however, such as elbow or bend losses, which generally form the upper end of the discharge pipe. In the Wisconsin experiments, the formulas of Dr. Lorenz have been modified to take account of losses due to elbows and bends. In computing experimental values of the coefficient of pipe friction and slip, a term has been introduced to correct

for the loss of energy due to friction in the air pipe.

Anderson's Theory.- A rather simple theory of the air lift pump was published by Mr. Robert M. Anderson in Bulletin No. 55 of the Hudson Engineering Company in 1905. Mr. Anderson assumed static conditions in developing this theory. Under these assumptions, the pressure at the air inlet due to the depth of submergence is equal to that produced by the mixture of air and water in the eduction pipe. The length of eduction pipe required to give a pressure equal to that due to the submergence is used as a means for computing the lift. This length is inversely proportional to the average density of the mixture. To find the latter quantity, an expression is developed for giving the mean volume of the air, while expanding isothermally from its volume at the inlet to its volume at atmospheric pressure.

Under the assumed conditions for developing his theory, Anderson takes no account for loss of head, due to entrance, pipe friction, slip, elbow loss, etc., and a constant must be introduced to take care of these losses.

Gibson's Theory.- In 1908, A. H. Gibson published his theory on the air lift pump in his "Hydraulics and Its Applications." His theory is based on the same fundamental principles as Anderson's except that it is not confined to static conditions. Mr. Gibson takes account of losses due to friction and velocity at exit.

Green's Theory.- Mr. Leonard M. Green published an article in the Engineering and Mining Journal of August 7, 1909, Volume 88, page 251, entitled, "Efficiency of the Air Lift as a Solution Pump." In this article he discusses mathematically his theory of the air lift pump. He discusses and gives formulae for the amount of air required, minimum air pressure, efficiency of the air lift under given conditions, etc. He makes one erroneous assumption when he says that the water and air in the eduction pipe are in layers; the layers of water being of equal volume and the layers of air being of equal weight. He has worked out formulas for computing the ratio of the volume of water and free air in each layer for given conditions of lift and submergence and for giving the number of these layers or the volumes of water and air discharged. He has also made no provision for entrance loss or loss at the elbow at the top of the discharge pipe which, in the opinion of the authors, is considerable, probably over 10 per cent.

By neglecting the above named losses, Green obtains theoretical efficiencies of over 90 per cent, and concludes that under proper conditions, the total combined efficiency of the compressor and lift should not be less than 70 per cent. Experiments do not substantiate this opinion.

Method of Operation.

A greater amount of air pressure is required to start the operation of an air lift pump than is required for normal operating conditions. When the air is first supplied for operating the pump, the air pressure should be greater than that due to the pressure of the air inlet, while after the discharge of the liquid from the pump has commenced, the pressure at the air inlet must be reduced by the amount of the entrance and velocity heads of the liquid entering the eduction pipe.

When a sufficient number of bubbles of air have entered the eduction pipe to raise the head through the entire lift, some of the liquid will be discharged over the top of the pipe. This loss of liquid in the pipe causes a reduction of pressure in the eduction pipe, which at times and under certain conditions allows a sudden influx of the air due to its high pressure,which may cause an exceedingly great loss of air in the compressed air tank and result in large losses. Following this, the liquid will regain its full static head, requiring the operation to be started over again.

The escape of air into the eduction pipe should be controlled to prevent this intermittent operation. The air should be throttled the moment the liquid begins to discharge. Pipe friction has a tendency to prevent this intermittent action, and in long pipes of small cross-section, it serves to some extent as a governor. This was found very noticeable in the experiments performed by the authors.

Advantages of the Air Lift Pump.

One of the principal advantages of the air lift pump is its dependability and freedom from breakdown. The only parts that require attention are the compressor and the receiver, and they are easily taken care of and repaired because they are located above ground. As a general rule, there is an emergency compressor, so that it can almost be stated that the pumps need never be shut down. There are no moving parts in the well to get out of order, and the life of the pump is almost indefinite.

In the common types of steam-acting pump, the working barrels, buckets, and plungers are a constant source of trouble and annoyance. They also interfere with the free movement of the water, while in the air lift pump there are no tees, bends, or valves, and the full area of the pump is available. This is a considerable advantage.

Under proper conditions, an air lift pump will discharge more liquid from a well of small bore than will any other type of pump made. The quantity that can be discharged by an air lift pump is only limited by the capacity of the well and the expense of pumping at unreasonably high rates.

Another distinct advantage of the air lift pump is its low maintenance cost. Because of its simplicity, the cost of maintenance is low. The fact that there are no moving parts in the well makes the pump especially suited for handling dirty or gritty waters, or corrosive liquids. Mechanical pumps suffer from fine sand in water, which cuts the packing, plungers, and valves, and makes frequent repairs

necessary. To repair such pumps means several days of shut-down with its expence and loss of time. The liquids of a corrosive nature may be pumped by the air lift pump because the pump and apparatus can be replaced at a small expense and loss of time. The air lift pump has also been used as a dredge pump with success.

The air lift pum can be used to considerable advantage in places where the wells are scattered over a considerable area, or are remote from the power house. In using deep well steam-driven pumps, a pump must be located at each well, and considerable loss in condensation occurs in transmitting the steam through long pipes to the pumps. The expense of such a plant is great because of the loss in steam and the attendance required. In the air lift pump the transmission loss is much less, and the well may be operated from the power house by valves, thus eliminating attendance.

Fluids of difference temperatures can be handled to advantage by the air lift pump in cases where the use of other types of pumps would be prohibited. In the case of pumping a hot liquid, the air absorbs part of the heat of the liquid, and hence is increased in volume, so that the discharge of liquid for the same expenditure of free air is greater with hot than with cold liquids. This results in a considerable gain in efficiency for the pump.

Another distinct advantage of the air lift is aeration. Aeration is one of the principal methods of water purification. Free sulphur gas or iron are eliminated from water by the air.

A precipitate of iron forms, which settles upon standing a short time. The air also oxidizes other impurities in the water and thus improves its quality.

Disadvantages of the Air Lift Pump.

Low Efficiency.- The low efficiency of the pump is often thought to be one of its serious disadvantages. If, however, the entire plant is considered, the duty developed compares very favorably with other deep well systems.

Great Depth of Submergence.- The air lift pump cannot be used in a shallow well or reservoir except to raise the water, or liquid, a very small distance, owing to the high percentage of the total length of the pump, which must be submerged to give good efficiencies. This fact limits the field of the air lift pump principally to deep well pumping.

Limited Horizontal Pumping.- Several plants have been installed where the air lift was used to pump water a considerable horizontal distance after it had been raised to the surface of the ground, but such plants are not efficient. The air in passing through the horizontal or even an inclined pipe, is not likely to be evenly distributed throughout the cross-section of the pipe, but is likely to pass along under the upper side, allowing a large space in the lower portion of the pipe for the water to slip back past the bubble. In a horizontal pipe, the air cannot make use of its buoyant effort to aid in discharging the water and overcoming friction, or its expansive force which helps to overcome pipe friction cannot be made use of effectively.

Aeration.- Aeration, although generally considered an advantage, is, under some conditions, a disadvantage. It promotes rusting and consequent destruction of the eduction pipe.

Conclusions Deduced from Work Already Performed on the Air-Lift Pump at the University of Wisconsin, 1908-09.

(1) The central air tube pump has the greatest theoretical capacity for a given size of well.

(2) The coefficient of pipe friction and slip decrease as the discharge increases, and decrease as the ratio of volume of air to volume of water increases.

(3) The coefficient of pipe friction and slip varies with the length of pump, but seems to be independent of the percentage of submergence and of the lift.

(4) The length of pump, the percentage of submergence and therefore the lift remaining constant, there is a definite quantity of air causing the maximum discharge. This quantity of air for maximum discharge, as also the ratio of volume of air to volume of water, differs for different percentages of submergence and lift, the length of the pump remaining constant.

(5) The length of pump remaining constant, the maximum output occurs at about the same percentage of submergence for all rates of air consumption, being from 61 to 65 per cent for the pump used in the Wisconsin experiments. At other submergences the output varies as the ordinate of a parabola having a vertical axis. Under these conditions, the lift does not remain constant as the submergence varies.

(6) The length of pump and percentage of submergence remaining constant, and therefore constant lift, the efficiency increases as the input decreases, - that is, the highest efficiencies are obtained at the lowest rates of pumping.

(7) By varying the percentage of submergence, and therefore the lift, the length of pipe remaining constant, the maximum efficiency is obtained at approximately 63 per cent submergence for all rates of input or discharge.

(8) The lift remaining constant, the efficiency increases as the percentage of submergence increases for all rates of input and all practical percentages of submergence.

(9) With the same size and type of pump, the percentage of submergence remaining constant, the efficiency increases as the lift increases for the small lifts experimented on, - that is, up to about 24 feet. From a theoretical study, however, the indications are that a point will be reached from which the efficiency will decrease as the lift increases.

(10) Other conditions remaining constant, there is no advantage to be gained by introducing compressed air above the surface of the water in the well.

(11) The type of foot-piece has very little effect on the efficiency of the pump, so long as the air is introduced in an efficient manner and the full cross-sectional area of the eduction pipe is realized for the passage of the liquid. Anything in the shape of a nozzle to increase the

kinetic energy of the air is detrimental.

(12) A diverging outlet which will conserve the kinetic energy of the velocity head increases the efficiency.

<u>Conclusions Deduced from the Experiments of Lange and Huerner on the Air-Lift Pump at The University of Wisconsin, 1910.</u>-

(1) The object of the foot-piece is not to thoroughly mix the air and water, but rather to provide a suitable entrance for each into the eduction pipe.

(2) The efficiency is not materially different for elaborate venturi or other fancy designed foot-piece than with the plain slotted type of foot-piece used in their experiments.

(3) The length of pump, the percentage of submergence, and therefore the lift remaining constant, there is a definite quantity of air causing the maximum discharge. This quantity of air for maximum discharge, as also the ratio of volume of air to volume of water, differs for different percentages of submergence and lift, the length of the pump remaining the same.

(4) By varying the percentage of submergence and therefore the lift, the length of pump remaining constant, the maximum efficiency is obtained between 70 and 80 per cent. The submergence for maximum efficiency increases with the size of pipe, as shown by the following values: 70 per cent submergence for the 1½" pipe, 75 per cent for the 2½" pipe, and 80 per cent for the 3" pipe.

(5) The lift remaining constant, the efficiency increases as the percentage of submergence increases up to 70 per cent.

(6) The larger the size of pump for a given length of eduction pipe, the greater the range of efficienc capacity, as is indicated by the flatter peak of the efficiency curve.

(7) The greater the per cent of submergence for a given length of eduction pipe, the greater the range of efficienc capacity.

(8) The quantity of water pumped per square foot of pipe area at maximum efficiency for a given submergence is the same for the $2\frac{1}{2}$ and 3-inch eduction pipe, but is about 20 percent less for the $1\frac{1}{2}$-inch pipe. However, an inference might be drawn that the efficienc rate of flow per square foot of pipe area will be approximately the same for larger sizes of pipe than have been used in these experiments. To find the most efficient rate of flow for sizes of pipe coming within the range of the curves plotted, multiply the actual area of the pipe in square feet by the value of $\frac{Q}{A}$ for the given submergence.

Object of These Experiments.-

The importance of the air lift pump in the commercial and industrial world, the great scarcity of literature and information on the subject, the difficulty surrounding its theoretical and mathematical analysis, and the great diversity of results has led to the study of the air lift pump.

The following experiments were undertaken primarily to determine the effect of various lengths of pipe on the performance of the air lift pump, and secondly to verify some of the conclusions reached in previous experiments on the air lift pump at The University of Wisconsin, when the conditions of operation were as nearly practical in regard to size of pipe and lift as the laboratory facilities offered.

CHAPTER II

DESCRIPTION OF APPARATUS

Definition of Terms.-

The notations and symbols used in the following discussions are given below.

"Reading" is the term used to designate a single value obtained by the inspection of the scale of an instrument.

"Run" is used to designate such a combination of readings, made under practically constant conditions, as to form a complete unit in the result.

"Series" is used to designate those runs made with varying rates of pumping, but with the same size of eduction pipe as regards length and diameter, and the same type of foot piece.

"Percentage Submergence" is the ratio of the distance the water level is above the point of air admittance to the distance the center of the discharge elbow is above the same point.

"Eduction Pipe" is the pipe through which the mixture of air and water flows.

"Lift" is the distance from the water level in the well to the center of the discharge elbow.

"Foot Piece" is that part of the pump in which the air and water are admitted to the eduction pipe.

"Slotted Foot Piece" is that particular design of foot piece shown in Fig. 3.

"Simple Foot Piece" is that particular design of foot piece similar to Fig. 3, except no slots were cut in it.

Foot-Piece.-

Manufacturers of air-lift pumps have made quite a bit of claim to the advantages of elaborate types of foot-piece for air lift pumps. They claim that greater efficiencies are obtained by the use of costly foot-pieces. It was believed by many that these claims were unfounded, and to corroborate their statements, numerous experiments were made with different types of foot-piece. Lange and Luerner performed experiments on several types , and found that the type of foot-piece had little to do with the efficiency of the pump. Their experiment follows:

"Before making the above series of runs, it was thought advisable to verify conclusion No. 11 previously deduced from experiments on the air lift pump at the University of Wisconsin, namely, that the type of foot-piece has very little effect on the efficiency of the pump, providing there is no great friction loss by forcing the air through small openings in the foot-piece. From a small glass model of the air lift pump erected in the laboratory, it was seen that no matter how thoroughly the air was mixed with the water at the foot-piece, the air immediately readjusted itself after leaving the foot-piece. This tends to show that the object of the foot-piece should not be to thoroughly mix the air and water, but to admit the air to the eduction pipe with the least loss due to friction.

"A series of runs were made at the Capitol heating plant on a 2½-inch eduction pipe, using the venturi foot-piece with

the air line connected directly to the foot-piece." (The foot-piece is shown in Figure 2 and the results in Figure 4 of their thesis.) "The air line to the foot-piece was then disconnected at the flange of the well casing. The series of runs taken under these conditions was with the $2\frac{1}{2}$-inch eduction pipe is shown on the data sheet. The results were erratic due to the intermittent working of the pump, which made the gages fluctuate greatly. Under these conditions, it was impossible to control the apparatus or to get a true reading of the gages.

"A series of runs was made, using the simple foot-piece. In this series of runs, as in all the remaining series, the air line extended only through the flange F (Figure 1)." (The same can be seen in Figure 2 of this thesis.) "The air and water entered together through the bottom of the foot-piece.

"Here again, the working of the pump was intermittent, and the apparatus could not be controlled, so the series of runs was abandoned. From the results of the few runs taken at 65 per cent. submergence, the writers are of the opinion that the efficiency would compare favorably with the other foot-piece used.

"It was decided to adopt some form of a simple foot-piece which could be easily and quickly made, and could be exactly reproduced with any size of pipe commonly used. The type decided upon was a foot-piece containing eight 1/8-inch longitudinal slots equally spaced around the diameter of the pipe. The details of this foot-piece are shown in Fig. 3. This type of foot-piece was used in the remaining series of

runs. The size of slots was the same for each size of pipe used, having a total slotted area of 9-1/2 square inches. The foot-piece for the various sizes of pipes were made by the writers from ordinary piping, the slots being cut in the shops of the University of Wisconsin with a 1/8-inch saw milling cutter. The bottom of the foot-pieces were leveled at a 45 degree angle to reduce the entrance loss of the water.

"A series of runs was then made with the slotted foot-piece. By comparing figures 4 and 6, it will be seen that the maximum efficiency of the complicated Venturi foot-piece and the simple slotted foot-piece is about the same for the same submergence and length of eduction pipe, but the Venturi foot-piece showed somewhat erratic results for low submergences. This verified conclusion No. 11 previously deduced from experiments at the University of Wisconsin, and was the reason for using the slotted foot-piece on the various sizes of eduction pipes.

"It was noted that with the air and water entering the eduction pipe through the same opening, the action was this: The water in the well casing would stand above the end of the simple foot-piece when the pressure of the air in the well casing was a minimum. But due to the air pressure, water alone would be forced into the eduction pipe. Gradually the air pressure would build up, lowering the level of the water in the well casing until the entire

inlet area to the eduction pipe would be exposed, when there would be an inrush of air into the eduction pipe. This would so lower the air pressure in the well casing that the level of the water would rise again to some level above the end of the eduction pipe and the above cycle of events would be repeated.

"In the case of the slotted foot-piece, the air pressure adjusted itself to a practically constant pressure. The water level in the well casing stood at such a height that a part of the slotted openings were exposed to the air, allowing enough air to escape through the eduction pipe to keep the air pressure in the well casing constant.

"After making the series of runs at the Capitol Heating Plant on the 2$\frac{1}{2}$-inch eduction pipe, the apparatus was moved to the Hydraulics Laboratory at the University of Wisconsin. The apparatus was then set up the same as at the Capitol Heating Plant, using 1$\frac{1}{2}$-inch eduction pipe of the same length, but with two exceptions. At the Capitol Heating Plant the air was supplied by an air compressor to a small receiving tank, carrying a pressure of about 90 pounds per square inch, then through a fairly long air line to the pump. It was deemed advisable to use a small air tank whose volume was one cubic foot in order to iron out any irregularities of air pressure. At the Hydraulics Laboratory, the air supply was taken directly from one of the large storage tanks of the University Pneumatic pressure waterworks plant. The small air tank from the Capitol Heating Plant was not

used, thereby securing a shorter air line from the air drum to the flange F (Figure 1)."

The above discussion, taken from Lange and Puerner's thesis, proves conclusively that the type of foot-piece has little to do with the efficiency of the pump. Consequently, the writers deemed it advisable to use the same simple slotted foot-piece used by Lange and Puerner for their experiments. The results obtained by Lange and Puerner and the conclusions in regard to the action of the air and water in the slotted foot-piece was verified by the writers. It was found that the water level in the well would so adjust itself that part of the slotted area of the foot-piece was exposed under running conditions, The area exposed varied only a few hundredths of a foot for the various lengths of pipe used and the various submergences.

The water was discharged from the elbow directly into the atmosphere. All gages were carefully tested and correction curves made for the same before any runs were made.

Well Casing.-

It was impracticable, if not impossible, to use an actual well, so the top of the well casing was cut off a short distance above the foot-piece, as shown in Figure 2. This prevented the water from rising to its normal height due to static pressure.

In the opinion of the writers, this departure from normal conditions did not affect the results of these experiments in any way. The well casing was made of ordinary 8-

inch piping with standard flanges screwed on both ends. The details are shown in Figure 2.

Eduction Pipe.-

It was originally planned to make a series of runs on 3-inch pipe of about 40, 80, 100, and 120 feet in length. The time, however, that could be spent on the experiment, together with the time lost in setting up and tearing down the apparatus, which was very difficult, due to the size and weight of the apparatus and the facilities on hand for handling the same, limited the experiment to 37, 80, and 100 feet of 3-inch pipe. Flange joints were used on the eduction pipe.

Water Supply.-

The water supply was obtained from the University mains by a 1½-inch pipe connection. The supply of water was measured by a calibrated Hersey Water Meter before it entered the well casing, and was controlled by the Valve V (Figure 2).

Air Supply.-

There were several possible ways of supplying air, one from the storage tanks of the University pneumatic water supply plant, or by the use of a separate compressor and tank. The former was decided upon, and the air supply was drawn from one of the storage tanks of the University pneumatic water supply

plant. The tank had a capacity of about 5000 cubic feet, and the pressure was maintained at about 90 pounds per square inch. A 3/4-inch pipe was used to conduct the air from the tank to the air drum. An automatic reducing valve was used to reduce the pressure to about 70 pounds per square inch. The amount of air entering the drum was controlled by valve V_2 (Fig. 2). The pressure on the two sides of the orifice was held steady by means of a valve on the air line near the foot-piece (V_3, Fig. 2).

The temperature of the air was measured by a thermometer and the pressure in the drum by a West gage, as shown in Fig. 2. A U-tube was used to measure the difference in pressure on the two sides of the orifice. An American pressure gage was used for measuring the pressure of the air entering the well casing.

The orifice plates were made of 1/16-inch sheet metal, and the diameter of the orifice was measured to one thousandth of an inch. Orifices of .281, .500, .707, 1.000, and 1.500 inches were used. The coefficients of the different orifices for various differences in pressure heads in inches of water was taken from curves drawn from data in Harris' book on "Compressed Air," page 130.

The pressure gages were all carefully calibrated, and the correction curves drawn. Corrected values, taken from these correction curves, were used in all computations.

In setting up the apparatus, all pipe connections were made air-tight by the use of white lead and heavy oil. All

connections were tested for air-tightness with soap solution while the pump was in operation and under maximum pressure before any data were taken.

Method of Observing.-

The following page shows a copy of the complete observed data taken in the various runs, and shows the form in which said data were taken:

Data Sheet -- College of Engineering, University of Wisconsin -- Sheet No.
Experiment on Air Lift Pump
Data by Krez and Barth. Computed by Krez and Barth.
Date December 9, 1920 Checked by ______________
General Data - 3" Eduction Pipe, Plain Foot-Piece, Air Gage 80', Water Gage 80.5',
70% Submergence, 1/2" Orifice. Barometer 28.94.

Run No.	Time	Water Meter Rdg. Cu.ft	Water Gage ft.pc. feet	Air Gage Feet	Air Gage on Orifice Drum #/sq.in.	Water U-Tube Ins. L	Water U-Tube Ins. R	Temp. C°	Surface Water in Well Feet	Gallons per Min.
1	2:41:50	52	56.5	55.5	31.0	0'-6.16"	0'-7.95"	19.5	2.41	28.37
			56.5	55.5	31.3	6.15	7.95			
	2:46:03	68	55.5	54.5	31.0	6.14	7.96	19.5		
Average			56.16	55.16	31.1	6.15	7.95	19.5		
2	2:54:40	14	56.5	56.0	30.3	5.70	7.40	19.5	2.42	44.3
			56.5	56.0	30.0	5.70	7.40			
	2:59:13	41	56.5	56.0	30.0	5.70	7.40	19.5		
Average			56.5	56.0	30.1	5.70	7.40	19.5		
3	3:07:55	99	56.5	56.0	43.5	5.69	7.44	19.5	2.42	51.6
			56.0	55.5	43.5	5.67	7.43			
	3:11:32	124	56.0	55.5	43.5	5.67	7.45	19.7		
Average			56.16	55.66	43.5	5.67	7.44	19.6		
4	3:16:57	66	56.0	55.5	41.8	5.15	7.95	19.8	2.42	63.1
			56.5	56.0	41.9	5.16	7.96			
	3:20:30	96	56.5	56.0	41.7	5.15	7.95	19.8		
Average			56.33	55.83	41.8	5.15	7.95	19.8		
5	3:28:03	46	56.0	55.0	44.8	6.00	7.10	19.8	2.42	40.15
			56.0	55.0	44.8	6.00	7.10			
	3:31:55	66	55.5	54.5	44.6	6.00	7.10	19.8		
Average			55.83	54.83	14.73	6.00	7.10	19.8		
6	3:45:50	03	56.0	55.5	29.9	6.38	6.75	19.8	2.41	15.1
			56.0	55.5	29.7	6.35	6.75			
	3:50:17	12	56.0	55.5	29.7	6.35	6.75	19.8		
Average			56.0	55.5	29.76	6.36	6.75	19.8		

Two men were required to take the data. One man took the readings of the gages while the other man recorded the data and made the few computations necessary at the time. When readings were practically constant, three readings of each instrument were taken over a period of four minutes. When the experiment was first started, six minute runs were taken until both writers became thoroughly familiar with the reading and could do it quickly. The length of run was determined by the second hand of a watch. The water U-tube readings were carefully read to one-hundredth of an inch.

In starting the pump the air valve V_2 (Figure 2) was always opened before turning on the water to prevent blowing of the water U-tube gage.

CHAPTER III

DEVELOPMENT OF FORMULAS USED

From "Compressed Air," by Harris.

A standard orifice, the same as is specified for water, that is, an orifice in a thin place made with sharp edges, was used for the measurement of air. A section of such an orifice is shown in section A-B, Figure 2. The conditions specified that the drop in pressure in passing through the orifice should not exceed much more than 6 inches of water. With this restriction, the change of temperature and of density of the air while passing the orifice may be neglected without appreciable error.

h - head of air of uniform density (w) that would produce the pressure i.

i - pressure head as found from the difference of the two U-tube water gage readings.

w - weight of a cubic foot of air at pressure P.

P - absolute pressure in pounds per square inch of air approaching orifice.

d - diameter of orifice in inches.

W - weight of air passing per second.

t - absolute temperature of air before orifice in degrees Fahrenheit.

C - experimental coefficient.

r - ratio of expansion of air.

P_1 - atmospheric pressure in pounds per square inch.

R - 53.37

G - gallons of water pumped per minute.

V - volume of free air in cubic feet per second, based on a pressure of 14.7 pounds per square inch and a temperature of 70° Fahrenheit.

Development of Formulas Used

Weight of Air Used in Pounds

When changes of temperature and of density can be neglected, the theoretical velocity through an orifice is:

$$v \text{ equals } \sqrt{2\,gh}$$

h equals $\frac{1}{12}\ \frac{62.4}{w}$, therefore v equals $\sqrt{29\ \frac{1}{12}\ \frac{62.4}{w}}$

But W equals wav_1, where a equals the area of the orifice in square feet, equals $\frac{d^2}{4x144}$

and W equals $\frac{d^2}{4 \text{ x } 144}\sqrt{2g\frac{1}{12}\ 62.4\ w}$

but w equals $\frac{144\ P}{53.35}$, therefore

W equals $.1639\ d^2\sqrt{\frac{1p}{t}}$

To this must be applied the experimental coefficient and

$$W \text{ equals } .1639\ d^2C\sqrt{\frac{1}{t}\ P}$$

For a .281 inch orifice W equals .01297 $c\sqrt{\frac{1}{t}}\,P$

For a .500 inch orifice W equals .041 $c\sqrt{\frac{1}{t}}\,P$

For a .707 inch orifice W equals .082 $c\sqrt{\frac{1}{t}}\,P$

For a 1.000 inch orifice W equals .164 $c\sqrt{\frac{1}{t}}\,P$

For a 1.500 inch orifice W equals .3696 $c\sqrt{\frac{1}{t}}\,P$

Energy in Air Based on Isothermal Expansion.-

Energy per gallon of water pumped equals pv $\log_e r$, equals $\frac{W}{G}$ Rt 2.303 $\log_{10} r$, equals

60 x 53.37 x 498.6 x 2.303 $\frac{W}{G}$ $\log_{10} r$ equals

3,677,000 $\frac{W}{G}$ $\log_{10} r$

$t = 40^{\circ}$ F.

Volume of Free Air Used.-

V equals $\frac{WRT}{Pa}$ equals $\frac{53.37 \times 529.6}{14.7 \times 144}$ x w, equals 13.32 w

Cubic feet of free air per gallon of water equals $\frac{V \times 60}{G}$

$T = 70^{\circ}$ F. P = 14.7 lbs. per sq.in.

Method of Computing.-

A Hersey water meter which had been previously calibrated measured the flow of the pump before the water entered the well.

A formula developed by E. Harris in his book on "Compressed Air", the development of which is shown under "Development of Formulas", was used to calculate the weight

of air used per second.

The water gage reading showed the height the water would rise above the gage if under atmospheric pressure. As the gage was .371 below the center of the slots in the foot-piece, this amount was subtracted from the water gage reading to get the reading of the height the water would stand in an actual well above the foot-piece.

The water gage reading minus .371 feet, divided by the total length of pipe above the foot-piece, gave the submergence.

The difference between the total length of pipe above the foot-piece and the height to which the water would rise in an open well gives the delivery head.

The ratio of expansion of the air in the pump was taken as the ratio of the air pressure on the foot-piece in pounds per square inch absolute to atmospheric pressure.

The energy of the air just before entering the foot-piece, per gallon of water pumped, is taken as the energy necessary to compress the air isothermally from atmospheric to gage pressure at the temperature of the water.

The product of the weight of air per gallon (8.34 pounds) and the delivery head in feet gives the work performed by the pump.

The ratio of the useful work done in pumping the water, to the theoretical energy of the air in expanding isothermally from the air gage pressure near the foot-piece to atmospheric pressure, is the efficiency of the pump.

The above method gives the efficiency of the pump from the time the air is about to enter. If the friction in the air

line is taken into consideration, the efficiency would be lower.

Sample Computations.-

Run #1 - Flow in Gallons per minute equals 14.62.

Gage pressure on orifice in pounds per square inch equals 31.67.

Absolute pressure on orifice in pounds per square inch equals 45.3 (Gage pressure plus barometric pressure).

Temperature of air, degrees Fahrenheit (absolute) equals 525.8.

Head difference on orifice, inches of water equals i, equals 4.38.

Coefficient of orifice (c) equals .6112, as obtained from curves of a plotted against absolute temperature.

$$\frac{ip}{t} \text{ equals } \sqrt{\frac{45.3 \times 4.38}{525.8}} \text{ equals } .6150$$

Weight of air in pounds per second equals w equals $.041\ C\sqrt{\frac{i}{t}P}$ for .500 inch orifice

equals .041 x .6112 x .6150

equals .01545 pounds.

Cubic feet of free air per second at 14.7 lbs. per square inch and 70° F. temperature equals 13.33 w equals 13.33 x .01545 equals .2060.

Cubic feet of free air per gallon of water equals

$$\frac{.2060 \times 60}{14.62} \text{ equals } .8455$$

Percent submergence equals $\frac{33.12 - 3.71}{81.63} = 40.1\%$

Delivery head equals 81.63-(33.12-37) = 48.92 ft.

$\frac{W}{G}$ pounds of air per gallon of water equals $\frac{.01545}{14.62}$ equals .001555 pounds.

Ratio of expansion of air equals $\frac{18.95 + 14.2}{14.2}$ equals 1.98

Logarithm of 1.98 equals .296.

Energy of expanding air per gallon of water pumped equals

$3{,}677{,}000 \times \frac{W}{G} \times \log_{10} r$

equals 3,677,000 x .01055 x .296 equals 1147.

Useful work per gallon of water pumped equals 8.34 x delivery head equals 8.34 x 48.92 equals 366 ft. lbs.

Efficiency in per cent equals $\frac{\text{useful work}}{\text{energy in air}}$ equals $\frac{366}{1147}$ equals 31.9%.

CHAPTER IV

A DISCUSSION OF EFFECT OF LENGTH OF EDUCTION PIPE UPON AIR-LIFT PERFORMANCE

The primary reason for these experiments was to determine the effect of length of eduction pipe upon air-lift performance. In view of this, Figures 10, 11, and 12 have been drawn to show more clearly what relation, if any, exists between length and efficiency.

It would be rather bold to lay down any definite laws or axioms based upon these experiments, as the range of lengths is too limited, the greatest length being 100.64 feet. Furthermore, data for only four different lengths are available, and hence it would be unwise to draw too sweeping conclusions from them.

Effect of Length Upon Efficiency.-

An explanation of Figure 10 will, perhaps, be of interest to the designer of a pump, as it shows the relation of maximum efficiency for each length, plotted against length of eduction pipe.

The curve is convex upward and parabolic in shape. The full line portion corresponds almost exactly to the equation $E = 13.9\ L^{.342}$. This equation was determined by plotting the points logarithmically. While this equation fits the experimental points very closely, when extended beyond them, as shown

by the dashed line, it tends to show efficiencies for the greater length which are, in the opinion of the authors, too high. Thus, at a length of 140 feet, this curve shows an efficiency of 75%, which is generally considered impossible for even the best-working air-lift.

The dotted line was drawn to show in some measure the authors' ideas on the subject. This curve would be practically flat at 150 feet of length. It is the opinion of the authors that at greater lengths than this, the efficiency will not increase.

Professor Gibson, in his text on hydraulics, states that with a given per cent. submergence and discharge, the efficiency remains practically constant for all lengths of the same sized pipe. If the data collected by the authors are correct (and we see no reason to doubt their truth), this statement is incorrect, at least for the lengths of pipe used by the authors.

Figure 12 shows an analysis based upon flow and percent submergence. These curves may be of interest to the designer, as they show that on the longer lengths, the high submergences are not as necessary for efficient operation as on the shorter lengths. If further investigation shows this to be true, it is of great importance, as a pump designed upon the old assumption that with a given flow and submergence, the efficiency remains constant for all lengths of pipe, the well might be built considerably deeper than necessary. Furthermore, higher pressures must be used for starting the pump for the high submergences.

This further shows that the air-lift is better for deep wells than shallow.

Effect of Length Upon Volume of Air at Foot-Piece.-

A rule which has been used by designers is that the volume of air per gallon at the foot-piece is the same for all lengths at any given flow and percent. submergence. The authors have attempted to investigate this, and the analysis of the problem is shown in Fig. 11.* The air consumption was taken from Figures 7, 8, and 9 at points of maximum efficiency, all of which occur at flows of between 40 and 60 gallons per minute.

An examination of this figure will show that this rule is true for all practical purposes on submergences above 50%, and also that it is more nearly true for the longer lengths on submergences below 50%. The curves tend to flatten out on the longer lengths, and it is probable that a point would be reached, even on the lower submergences, where the rule would be true.

These curves further show that the efficiency increases with the length.

* The volume was computed for the pressure corresponding to that in the foot-piece as shown by the gage and at a temperature of about 38° Fahrenheit.

CHAPTER V

CONCLUSIONS

The primary object of these experiments is to determine the effect of various lengths of eduction pipe upon air-lift performance. They are intended to be of value to the designer as well as to the student of the phenomena. From them, ideas as to the practical usefulness of the pump may be better understood, and thus the field of usefulness of the pump may be more definitely limited.

With the idea in view, conclusions have been drawn as to the following: (1) length, (2) volume of air, (3) percentage of submergence. These conclusions are intended to embrace only the size and type of apparatus used, and are not expected to cover the entire scope of the pump, as the data on which they are based is limited.

(1) The efficiency of the pump increases with, but not in direct proportion to the length of eduction pipe. This is true for all submergences and all discharges, and all lengths within the range of these experiments.

It is the opinion of the authors that this increase is not indefinite, but that a point will be reached at which an increase in length will cause a decrease in efficiency. From what little data we have, it is our opinion that this point will be reached at about 150 feet in length.

(2) The amount of air used per gallon decreases with, but not in direct proportion to the length of eduction pipe. This is true for all submergences, but is more marked on the

low submergences.

By increasing the flow of air, the discharge of the pump is increased up to a point where a further increase in quantity of air causes a decrease in discharge. This effect probably occurs in all lengths of pipe, at all submergences, but was only noticed on the 37-foot length at 40 and 50 per cent. submergences. This point was reached at a flow of 73.35 gallons per minute for the 50 per cent. submergence and at a flow of 59.25. gallons per minute for the 40 per cent. submergence.

It is the authors' opinion that this is due to the air occupying so much space in the pipe as to leave only a small space for the water, and thus so much decreasing the effective area of the pipe as to decrease the flow in it.

(3) By increasing the submergence the amount of air used is decreased. The efficiency is also increased until a submergence of about 70 per cent. is obtained, when it tends to decrease with further increase in submergence. The efficiency remains practically constant, between 60 and 70 per cent. submergence. (Figures 4, 5, 6.)

(4) That the longer the pump, the greater the range of efficient operation.

(5) The longer the pump, the lower the submergence required for efficient operation.

(6) The longer the pump, the greater the delivery from a given size of pipe.

APPROVAL

The foregoing thesis is hereby approved as a creditable study of an engineering subject, carried out and presented in a manner sufficiently satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is to be understood that by this approval the undersigned does not necessarily endorse or approve any statement made, opinions expressed, or conclusions drawn therein, but approves the thesis only for the purpose for which it is submitted.

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Assistant Professor
(Title)

SERIES I - 3-INCH EDUCTION PIPE, LENGTH 81.63 FEET - PLAIN SLOTTED FOOTPIECE

Run No.	Flow in Gals per Min.	Absolute Press. on Orifice #/sq.in.	Temp. of Air °F. Abs.	i Head Diff on Orifice in Water	(c) Coefficient of Orifice	w Lbs air per sec.	Cu.ft. free air p=14.7 #/sq.in t=70°F	Cu.ft. free air per gal. water	% Submergence	Delivery Head	r	Energy of Expansion	Useful Work per gal.	Efficiency
1	14.62	45.3	525.8	4.38	.6112	.01545	.206	.8455	40.1	48.92	1.98	1147	366	31.9
2	21.25	47.5	525.8	7.49	.6164	.0208	.2775	.784	40.3	48.72	1.95	1040	366	35.2
3	31.03	47.2	520.6	1.30	.6016	.0349	.466	.900	39.0	49.82	1.92	1160	415	35.3
4	37.38	37.3	520.6	2.45	.6039	.0414	.553	.800	38.9	49.92	1.945	1180	416	35.3
5	67.9	36.4	520.6	6.57	.6083	.0675	.900	.795	38.8	50.02	1.95	1185	417	35.2
6	52.5	38.1	524	4.86	.6069	.0592	.790							
7	24.12	57.9	525	2.14	.6056	.0121	.162	.404	50.2	40.68	2.24	645	338	52.5
8	27.26	44.8	524	4.46	.6113	.01543	.206	.454	50.2	40.68	2.24	726	338	46.5
9	47.87	61.9	524											
10	37.1	50.0	524	5.82	.6147	.01875	.250	.404	50.4	40.08	2.21	640	334	52.1
11	16.95	52.6	527	1.97	.6050	.0110	.147	.520	49.7	41.48	2.21	823	345	42.0
12	50.74	44.6	525	.73	.6005	.0239	.319	.377	49.3	41.18	2.24	594	343	57.3
13	64.4	40.6	524.4	1.37	.6017	.0321	.429	.400	49.5	39.68	2.28	658	332	50.5
14	95.13	50.4	524	6.68	.6087	.0800	1.069	.673	51.5	39.18	2.32	1242	327	26.3
15	76.95	46.0	523	3.79	.6058	.0574	.765	.5975	49.5	41.48	2.24	956	345	36.1
16	65.7	45.1	524	.600	.6002	.0227	.303	.277	59.1	33.3	2.445	490	277	56.5
17	88.3	49.7	524.2	1.160	.6011	.0327	.437	.296	60.2	31.5	2.47	532	263	49.5
18	37.3	40.6	532.8	2.41	.6063	.01295	.1725	.2775	62.7	28.3	72.54	515	236	45.7
19	44.8	46.3	532.8	3.55	.6093	.0139	.186	.249	60.7	31.1	2.49	451	259	57.5
20	50.7	50.7	532.8	4.51	.6106	.0161	.215	.254	59.0	31.4	2.49	463	261	57.6
21	59.0	56.5	532.8	5.64	.6142	.0190	.253	.257	60.2	32.3	2.49	468	269	57.5
22	26.6	46.1	524	1.40	.6030	.00868	.116	.262	60.7	31.02	2.57	471	259	55.0
23	19.4	50.1	524	.85	.6016	.00705	.0951	.291	60.7	31.02	2.57	523	259	49.5
24	14.4	54.9	524	.42	.6003	.00516	.069	.289	60.7	31.02	2.58	520	259	49.5
25	27.8	44.5	527	1.80	.6044	.00967	.1195	.258	69.8	23.58	2.56	520	196.5	37.8
26	43.7	43.3	527	1.70	.6040	.00925	.1235	.1695	69.8	23.58	2.72	338	196.5	58.0
27	51.1	56.6	528	1.76	.6042	.0108	.1440	.1689	69.6	23.78	2.71	336	198	59.0
28	62.5	54.9	528	1.80	.6044	.01068	.1425	.1370	69.6	23.78	2.71	272	198	72.8
29	39.6	57.8	528	1.10	.6023	.0086	.1145	.1735	69.6	23.78	2.68	341	198	58.2
30	14.8	42.8	528	.40	.6001	.00493	.0591	.2395	69.4	24.00	2.70	526	200	38.0
31	83.5	42.1	524.6	.43	.5998	.01715	.0290	.1645	69.4	24.00	2.70	326	200	61.3

SERIES I - 3-INCH EDUCTION PIPE, LENGTH 81.63 FEET - PLAIN SLOTTED FOOTPIECE

Run No.	Flow in Gals. per Min.	Absolute Press. on Orifice #/sq.in.	Temp. of Air °F Abs.	i Head Diff. on Orifice in Water	(c) Coefficient of Orifice	w Lbs air per Sec.	Cu.ft. free air p=14.7 #/sq.in t=70°F	Cu.ft. free air per gal. water	% Submergence	Delivery Head	r	Energy of Expansion	Useful work per Gal.	Eff.
32	21.3	43.2	526.8	.38	.6001	.00435	.0582	.1645	75.0	20.58	2.84	340	171	50.5
33	28.8	44.6	526.8	.58	.6008	.00547	.0730	.1520	74.5	20.88	2.84	326	174	53.4
34	40.55	47.2	526.8	.81	.6014	.00664	.0885	.1305	75.2	19.9	2.84	271	166	61.3
35	50.8	52.9	526.8	1.14	.6024	.00834	.1110	.1300	75.0	20.6	2.84	272.5	171	62.6
36	59.5	54.7	526.8	1.72	.6042	.01045	.1395	.1405	75.0	20.6	2.84	292.0	171	58.5
37	75.6	53.6	526.8	2.70	.6070	.01310	.1750	.1390	75.2	19.9	2.84	288.0	166	57.6
38	89.5	56.2	526.8	4.27	.6110	.01690	.2255	.1510	75.0	20.6	2.84	314.0	171	54.5
39	41.1	47.2	527	.58	.6008	.00535	.0686	.1015	79.4	16.9	2.92	221	141	63.9
40	26.5	44.2	527	.30	.600	.00393	.0525	.1190	80.4	16.0	2.97	251	133.5	53.2
41	51.8	51.9	527	.75	.6012	.00669	.0891	.1035	79.9	16.5	2.93	222	137.5	62.0
42	62.4	51.5	527	1.08	.6022	.00802	.1070	.1030	80.3	16.4	2.90	219	136.8	62.3
43	79.5	53.2	527	1.88	.6046	.01115	.153	.1155	80.0	16.3	2.96	242	135.9	56.2
44	91.0	50.2	527	3.01	.608	.0133	.178	.1170	79.9	16.6	2.96	254	138.2	54.5
45	39.	32.5	533.6	3.05	.6050				39.6	49.35				
46	56.2	46.7	527	6.04	.6080	.0729	.965	1.030	39.0	49.8	2.34	1760	415	23.6
47	39.9	37.2	533.7	2.31	.6036	.03985	.528	.795	39.4	49.52	1.995	1100	413	37.6
51	57.5	56.4	528.3	4.65	.6066	.07010	.930	.970	40.5	48.62	2.075	1420	405	28.5
47	22.4	41.2	533	.18	.3995	.00579	.0773	.207	69.8	24.68	2645	401	206	51.4
48	46.8	45.7	533	.45	.6000	.00968	.1295	.166	69.6	24.8	2655	322	206.5	64.1
49	56.5	46.9	533	.67	.6006	.01195	.1595	.1690	70.2	24.32	2655	330.5	202	61.0

SERIES II - 3-INCH EDUCTION PIPE, LENGTH 100.64 FEET

Run No.	Flow in Gals Per Min.	Absolute Press. on Orifice #/sq.in	Temp. of Air °F Abs.	i Head Diff. on Orifice in Water	(c) Coefficient of Orifice	W Lbs. Air per Sec.	Cu.ft. free air p=14.7 #/sq.in. t=70°F.	Cu.ft. free air per Gal. Water	% Submergence	Delivery Head	r	Energy of Expansion	Useful Work per Gal.	Efficiency
5	36.4	42.7	523	.37	.6000	.01705	.228	.376	50.4	50.0	2.57	705	417	59.1
6	51.1	44.0	527.4	.78	.6004	.02620	.350	.410	50.4	50.0	2.53	755	417	55.3
7	60.6	49.0	528.3	1.24	.6015	.03340	.446	.441	49.7	50.5	2.515	818	420	51.5
11	19.35	43.7	534.6	2.60	.6068	.01149	.1531	.475	50.4	50.0	2.515	756	417	55.1
12	35.4	54.6	534.6	5.10	.6130	.01830	.2440	.411	50.4	50.0	2.515	756	417	55.1
18	74.9	47.2	526.6	2.49	.6040	.04690	.626	.503	50.4	50.0	2.53	925	417	45.1
19	94.6	44.9	524.0	7.78	.6093	.08150	1.090	.690	50.8	49.5	2.59	1310	412	31.5
16	32.6	51.2	533	1.00	.602	.00763	.102	.188	70	29.98	3.09	422	250	59.3
17	18.6	45.5	533	0.50	.601	.00993	.0660	.213	70.1	29.78	3.115	477	248	52.0
25	50.0	50.0	532	0.49	.6004	.01060	.1415	.1695	71.5	28.64	3.15	389	239	61.4
26	68.0	54.3	536.4	0.84	.6010	.01440	.192	.170	70	29.98	3.09	382	250	63.6
27	84.1	53.3	536.4	1.49	.6026	.01890	.252	.1798	70.2	29.68	3.13	409	247.5	60.5
34	27.4	52.9	533	.25	.5998	.00386	.0515	.1125	80.4	19.98	3.44	278	166.5	60.0
35	36.8	55.0	533	.46	.6004	.00520	.0695	.1131	79.9	20.48	3.40	276	171.0	62.0
36	51.6	57.3	533	.72	.6012	.00687	.0916	.1065	80.4	19.98	3.45	263	166.5	63.3
37	63.8	62.6	534	1.15	.6024	.00885	.1182	.1015	80.0	20.18	3.42	271	168.0	62.0
38	81.5	62.1	533	1.97	.605	.01190	.1590	.1170	80.5	19.60	3.45	288	164.0	57.0
42	8.20	53.7	533	2.31	.6074	.00376	.0502	.490	69.8	30.3	3.10	830	252	30.2
43	8.25	52.4	533	1.43	.6046	.00291	.0388	.282	75.2	25.0	3.26	666	208	31.2
44	10.15	52.5	533	.88	.6023	.00231	.03085	.1830	80.2	19.0	3.46	453	158	34.9
45	8.53	55.2	533	2.31	.6060	.01205	.1610	1.131	39.4	61.0	2.17	1760	506	29.2

SERIES II - 3-INCH EDUCTION PIPE, LENGTH 100.64 FEET - PLAIN SLOTTED FOOTPIECE

Run No.	Flow in Gals. per Min.	Absolute Press. on Orifice #/sq.in.	Temp. of Air °F Abs.	i Head Diff. on Orifice in Water	(c) Coefficient of Orifice	W Lbs. Air per Sec.	Cu.ft. free air p=14.7 #/sq.in. t=70°F.	Cu.ft. free air per Gal. Water	% Submergence	Delivery Head	r	Energy of Expansion	Useful Work per Gal.	Eff.
1	22.35	35.75	534.6	.69	.6004	.01980	.2643	.706	40.4	59.98	2.23	1132	500	44.2
2	38.80	42.75	535.6	1.33	.6017	.03219	.4299	.664	40.7	58.98	2.26	1082	492	45.4
3	49.65	44.45	531.8	3.24	.6052	.0505	.6740	.814	39.8	60.18	2.28	1345	502	37.3
4	58.60	48.05	527.4	5.39	.6074	.0699	.9340	.955	40.0	59.63	2.26	1595	498	31.3
10	75.50	62.25	528.0	5.45	.6030	.0816	1.089	.865	40.6	59.18	2.58	1568	493	31.5
13	20.81	57.10	533.2	1.00	.602	.00834	.1110	.320	59.6	41.04	2.82	663	342	51.6
14	38.90	53.15	533.6	3.00	.6079	.01365	.1820	.261	59.2	40.64	2.78	570	338.5	59.4
15	53.80	57.30	532.8	4.88	.610	.01815	.2420	.270	59.6	41.04	2.81	555.5	342	61.5
21	61.75	40.10	528.3	.52	.6001	.01956	.2610	.254	59.6	41.04	2.81	521.0	342	65.7
23	72.40	52.45	531.0	.63	.6002	.0246	.3280	.272	59.4	40.84	2.80	578.0	341	65.8
24	89.30	44.75	531.0	1.65	.6023	.03682	.4910	.340	59.5	40.94	2.78	670	341.5	51.0
28	63.4	50.4	536.4	.56	.6003	.0113	.1510	.1430	74.45	26.19	3.25	330	218	66.1
29	79.1	53.4	536.0	.87	.6010	.01453	.1940	.1470	74.55	26.09	3.26	345.8	219.5	63.5
30	86.3	50.9	536.4	1.02	.6013	.01538	.2050	.1425	74.55	26.09	3.29	338.5	219.5	64.8
31	25.6	53.2	533.0	.40	.6002	.004915	.06550	.1535	74.75	25.89	3.26	362.1	216.0	59.7
32	34.9	51.6	533.0	.70	.6011	.00617	.08106	.1390	74.80	25.84	3.26	333.0	216.0	65.5
33	52.5	62.05	533.0	1.25	.6027	.00933	.12450	.1190	74.75	25.89	3.26	333.0	216.0	65.5
39	54.9	39.45	525.5	.88	.6004	.0555	.740	.811	40.4	60.24	2.24	1301	503	38.6
40	8.22	53.15	531	9.33	.626	.00785	.1050	1.435	50.4	50.24	2.49	140.2	41.9	29.85
41	8.25	69.15	532.5	4.00	.613	.00573	.0763	.555	58.8	41.84	2.77	112.5	34.85	31.0
46	74.0	39.85	525.5	5.08	.6032	.1377	1.840	1.490	41.4	59.24	2.40	2610	594	18.9
47	60.0	40.95	532	.52	.6006	.01560	.2080	.2080	60.55	40.09	3.18	478.5	334	68.3
48	91.15	42.95	530	1.94	.6049	.0311	.4150	.2730	59.75	40.89	3.155	570.0	341	59.8
49	77.2	47.10	530	.95	.6018	.02268	.3030	.2360	59.60	41.04	3.16	538	342	63.5

SERIES III - 3-INCH EDUCTION PIPE, LENGTH 37.85 FEET, PLAIN SLOTTED FOOTPIECE

Run No.	Flow in Gal. per Min.	Absolute Press. on Orifice #/sq.in	Temp. of Air °F Absolute	(i) Head Diff. on Orifice in Water	(c) Coefficient of Orifice	W Lbs. Air per Sec.	Cu.ft. of free air p=14.7 #/sq.in. t=70°F	Cu.ft. free air per Gal. Water	% Submergence	Delivery Head	r	Energy of Expansion	Useful Work per Gal.	Efficiency
1	13.35	52.3	529.0	4.34	.6110	.01641	.2190	.986	43.7	21.29	1.49	782.4	172.5	22.1
2	23.00	50.7	527.0	9.89	.6440	.0256	.3420	.888	44.0	21.19	1.475	684.0	175.0	25.7
35	34.30	52.5	528.0	1.28	.6015	.0346	.4610	.802	41.5	22.19	1.46	610.0	184.5	30.3
36	47.3	58.9	527.0	3.13	.6050	.0585	.7800	.988	41.6	22.05	1.49	790.0	183.3	23.3
37	62.4	62.5	525.3	5.46	.6074	.0800	1.065	1.025	44.0	21.19	1.485	815.0	176.3	21.4
43	58.5	56.0	522.0	6.41	.6030	.1850	2.470	2.530	43.1	21.55	2.040	3160	171.0	5.42
6	7.06	25.6	526.	0.96	.6019	.00533	.0711	.604	60.4	15.0	1.645	602	125	20.8
7	18.77	28.3	527.	2.44	.6063	.00875	.1170	.374	59.8	15.9	1.642	369	132.7	36.1
8	28.97	33.8	527.	3.17	.6083	.01120	.1495	.309	59.8	15.9	1.655	311	132.7	42.7
9	51.50	52.0	528.	5.09	.613	.0178	.238	.377	60.5	14.9	1.665	283	124.2	44.0
10	62.05	50.0	527.7	8.35	.6206	.0228	.340	.329	61.3	14.65	1.683	305	122.1	40.2
11	37.90	42.2	528.0	3.75	.6097	.01370	.183	.290	61.9	14.4	1.683	301	120.4	40.0
51	99.60	59.2	526.5	3.60	.6056	.0631	.843	.577	61.6	14.5	1.713	545	121.0	22.2
52	85.2	42.0	525.0	2.45	.6039	.0439	.585	.412	60.5	15.1	1.687	432	126.0	29.2
53	70.03	35.35	524.0	1.95	.6019	.0359	.479	.4095	57.8	15.0	1.642	406	125.1	30.8
19	88.6	44.3	529	7.35	.6184	.0197	.2630	.1595	74.7	9.50	1.225	222	79.1	35.6
20	81.55	49.2	529	4.66	.6120	.0166	.222	.1571	74.8	9.56	1.840	198	79.7	40.2
21	72.5	50.6	529	3.21	.6084	.0133	.1845	.1468	74.7	9.50	1.833	184.5	79.1	42.9
22	57.4	37.6	529	2.79	.6073	.0111	.1483	.1545	73.2	10.09	1.804	182.0	84.0	46.1
23	43.1	44.3	529	1.30	.6030	.00815	.1088	.1518	73.5	10.03	1.804	177.5	83.7	47.2
24	25.4	29.4	529	.92	.6018	.00575	.0779	.1835	73.2	10.10	1.800	213.5	84.2	39.0
46	5.89	36.8	527	1.69	.6054	.00270	.0360	.3670	74.4	9.7	1.804	442.0	81.0	18.35
47	14.00	47.1	527	2.30	.6074	.00349	.0466	.2005	74.7	9.5	1.825	239.0	79.3	33.2
25	96.5	59.8	533	3.95	.6122	.0162	.221	.1373	79.9	7.60	1.91	173	63.4	36.6
26	65.6	45.3	532	2.77	.6072	.0120	.160	.1380	80.6	7.27				
27	69.8	38.7	532	2.10	.6054	.00967	.1290	.1110	79.6	7.70	1.895	141.5	64.1	45.3
28	94.4	49.5	531.2	4.32	.611	.01590	.2125	.1350	79.6	7.70	1.90	173.0	64.1	37.1
29	70.7	35.6	530.5	2.38	.6062	.01005	.1340	.1140	29.6	7.70	1.895	145	64.1	44.2
30	50.6	41.3	531	.90	.6018	.00670	.0894	.1060	80.1	7.53	1.88	134	63.8	47.6
31	34.8	33.4	530.5	.53	.6006	.00457	.0601	.1038	80.6	7.30	1.91	134.2	60.8	45.3
32	53.5	46.3	530.5	.88	.6017	.06683	.0913	.1025	80.0	7.63	1.915	132.5	63.6	48.0

SERIES III - 3-INCH EDUCTION PIPE, LENGTH 37.85 FEET, PLAIN SLOTTED FOOTPIECE

Run No.	Flow in Gal. per Min.	Absolute Press. on Orifice #/sq.in.	Temp. of Air °F Absolute	(i) Head Diff. on Orifice in Water	(c) Coefficient of Orifice	w Lbs. Air Per Sec.	Cu.ft. of free air p=14.7 #/sq.in. t=70°F.	Cu.ft. free air per Gal. Water	% Submergence	Delivery Head	r	Energy of Expansion	Useful Work per Gal.	Efficiency
33	61.0	43.4	530.7	1.36	.6030	.00823	.1097	.1080	79.6	7.70	1.91	139.5	64.1	46.0
34	73.5	44.8	530.7	2.12	.6053	.01060	.1415	.1152	79.5	7.74	1.892	145.0	64.5	44.5
48	8.26	32.5	530	1.43	.6045	.00232	.0310	.2250	79.6	7.70	1.88	293.	64.1	21.9
49	16.93	34.3	530	1.66	.6052	.002575	.0344	.1218	83.3	6.29	1.91	156.5	52.4	33.5
50	22.6	39.3	530	2.73	.6088	.00355	.0475	.1260	80.0	7.56	1.89	164.	63.0	38.4

SERIES III, 3-INCH EDUCTION PIPE, LENGTH 37.85 FEET - PLAIN SLOTTED FOOTPIECE

Run No.	Flow in Gals. Per Min.	Absolute Press. on Orifice #/sq.in.	Temp. of Air °F Absolute	i Head Diff. on Orifice in Water	(c) Coefficient of Orifice	W Lbs air Per Sec.	Cu.ft. free air p=14.7 #/sq.in. t=70°F.	Cu.ft. free air per Gal. Water	% Submergence	Delivery Head	r	Energy of Expansion	Useful Work per Gal	Efficiency
3	6.01	31.35	524.0	1.69	.6040	.00792	.1058	.1055	50.5	18.77	1.558	931	156.5	16.81
4	16.35	34.45	524.0	3.82	.6095	.01235	.1650	.0570	50.7	18.70	1.558	502.5	156	31.03
5	33.65	57.85	524.5	7.02	.6176	.02230	.2980	.0531	50.1	18.94	1.558	467.5	158.1	33.80
38	79.00	68.55	524.5	8.07	.6111	.10560	1.4100	.1070	52.0	18.19	1.697	1137	157.8	13.89
39	69.25	48.15	523.5	4.39	.6064	.06350	.8475	.0735	50.7	18.70	1.597	684	156.0	22.80
40	58.00	58.35	524.0	1.91	.6028	.04560	.6085	.0630	49.4	19.19	1.563	561.5	160.0	78.50
41	47.60	51.15	524.0	1.06	.6011	.03170	.4230	.0532	49.4	19.19	1.558	484	160.0	33.05
42	72.60	57.35	525.0	6.48	.6083	.08390	1.1200	.09250	52.0	18.19	2.115	1380	151.8	11.00
12	20.54	30.35	528.	.80	.6014	.00523	.0699	.2054	70.7	11.11	1.779	2312	92.60	40.1
13	35.22	43.35	528.	1.17	.6025	.00771	.1043	.1790	70.7	11.19	1.765	198.0	93.35	47.1
14	49.35	47.35	529.	2.30	.6059	.01127	.1505	.1826	69.6	11.49	1.775	204.5	95.75	46.85
15	58.90	46.15	529	3.35	.6088	.01348	.1800	.1832	70.7	11.19	1.765	207.	93.35	45.10
16	73.30	51.15	529	5.76	.6126	.01875	.2505	.20500	70.1	11.29	1.765	232.	94.10	40.60
17	98.00	73.85	529.5	9.08	.6226	.2860	3.8200	2.340	71.9	10.59	1.791	271.5	96.60	35.60
44	10.33	44.15	527.5	3.38	.6190	.0135	.1820	1.055	69.05	11.69	1.746	1161	97.50	8.39
45	5.97	44.15	527.5	2.37	.6076	.01109	.1415	1.410	69.05	11.69	1.746	1652	97.50	5.89